Towards a space-borne quantum gravity gradiometer: progress in laboratory demonstration

<u>Nan Yu</u>

James M. Kohel

James R. Kellogg

Lute Maleki (PI)

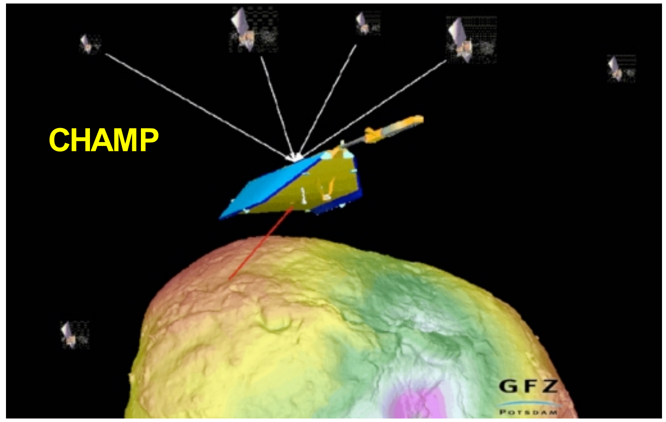
Jet Propulsion Laboratory

California Institute of Technology

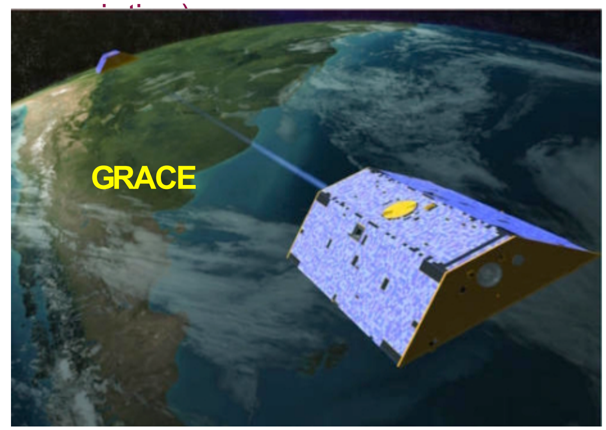
Pasadena, CA, USA

Goal
Advanced Gravity Missions

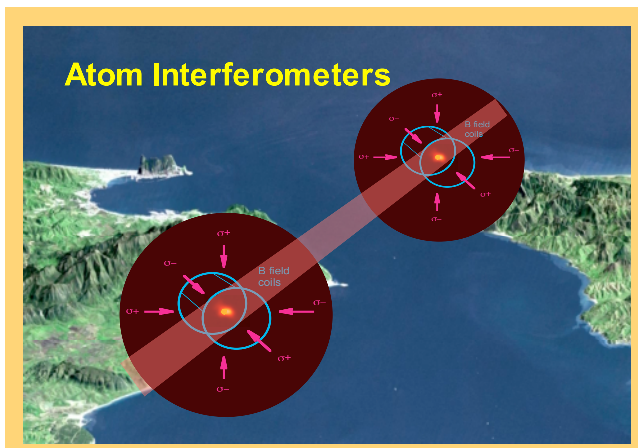
GPS-CHAMP high-low satellite-to-satellite and ground based laser tracking



Low-low satellite-to-satellite microwave tracking and ranging (for long wavelength i.e. 500 km and time



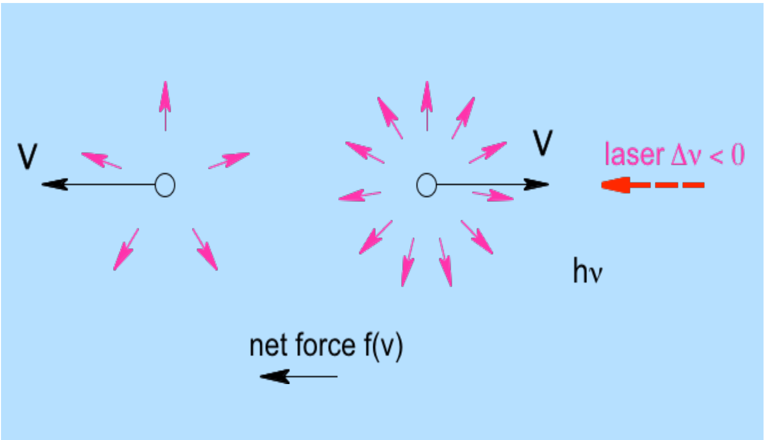
GOCE satellite gradiometry using 3-axis accelerometers (for high resolution ,i.e. 100 km)



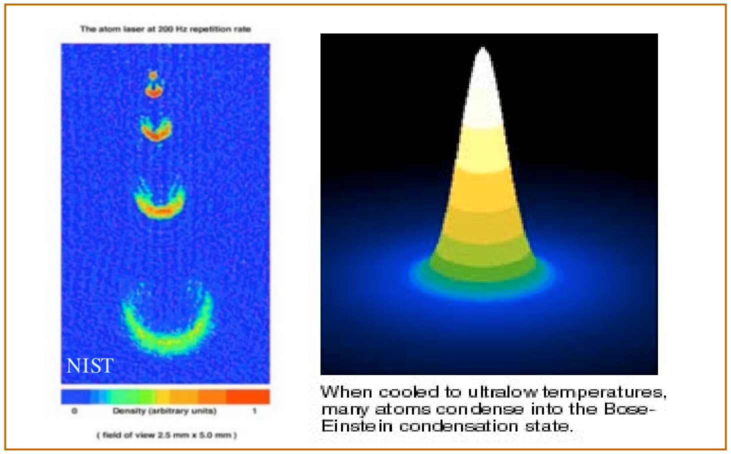
Quantum gravity gradiometer using cold atoms as truly drag-free test masses (high spatial resolution + high stability for time variation)

Technology Background
Laser Control and Manipulation of Atoms

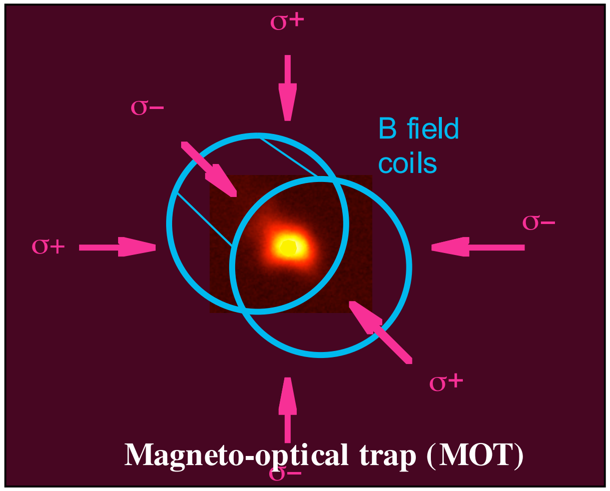
Laser cooling



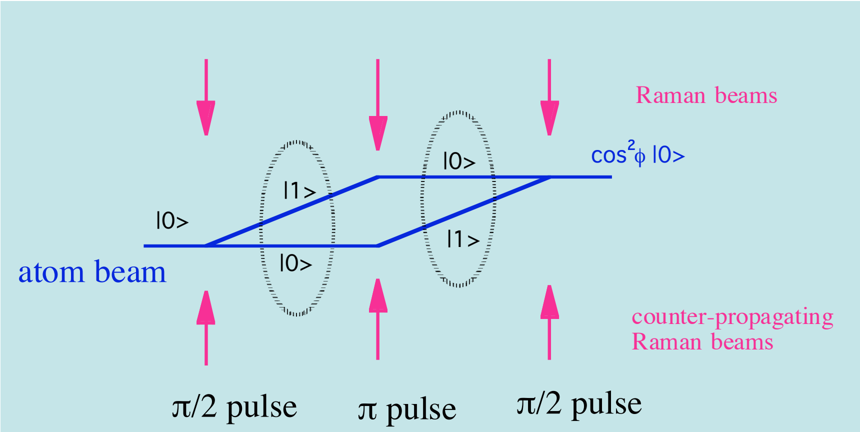
Bose-Einstein condensate and atom lasers



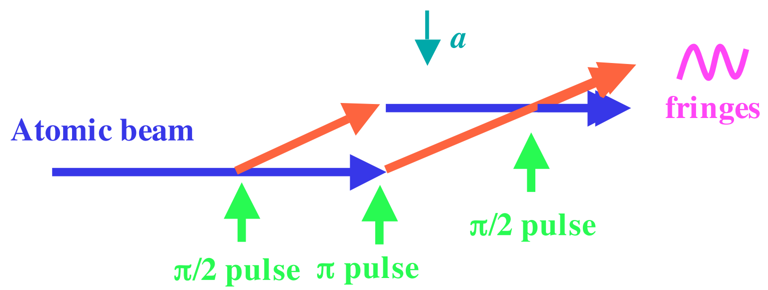
Laser trapping



Atom interferometry and atom optics



Working Principle
AI Accelerometer and Gradiometer



The phase difference of two atomic beam paths at the end of 2nd π/2 pulse:

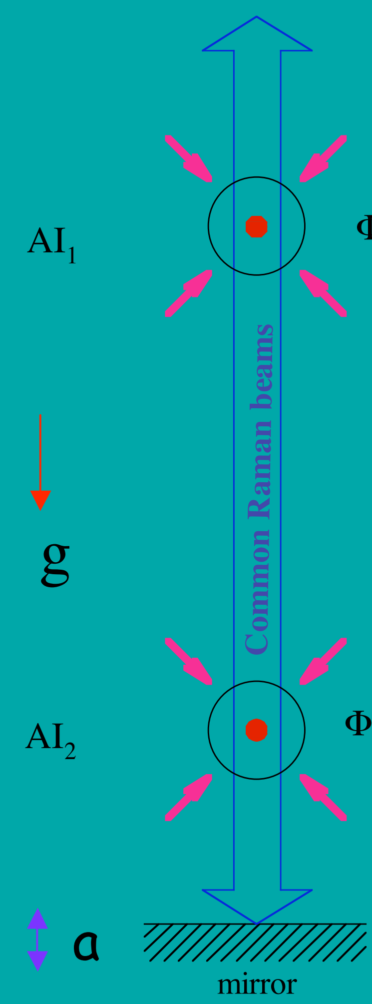
$$\Delta\Phi = 2\,k\,a\,T^{2}$$

where k is the laser wavenumber and T is the interaction time.

Laboratory measurements:
- with over 10^6 atoms, the shot-noise limited SNR ~ 1000, per launch sensitivity: $10^{-11}/T^2\ g$.
- demonstrated resolution: $10^{-11}\ g^{\dagger}$.

† A. Peters, K. Y. Chung, and S. Chu, Metrologia 38 , 25 (2001).

The common reference acceleration is cancelled out, the suppression has been demonstrated to be greater that 140 dB*.



$\Phi_1 = 2k(g_1+a)T^2$

$\Delta\Phi_{12} = 2k\,(g_1-g_2)\,T^2$

$\Phi_2 = 2k(g_2+a)T^2$

Ground based gradiometer has been demonstrated at 10 E level.*

*M. J. Snadden et al. PRL **81**, 971 (1998).

Why in Space
Greatly Enhanced Gradiometer Performance

$$\delta g = (\pi/\mathrm{SNR})/2kT^2$$

In absence of a large gravity acceleration, the cold atoms (test masses) are floating freely with little average drift velocity, allowing very long interrogation time ($\geq$10 s). This greatly increases the intrinsic sensitivity, because of the $1/T^2$ dependence.

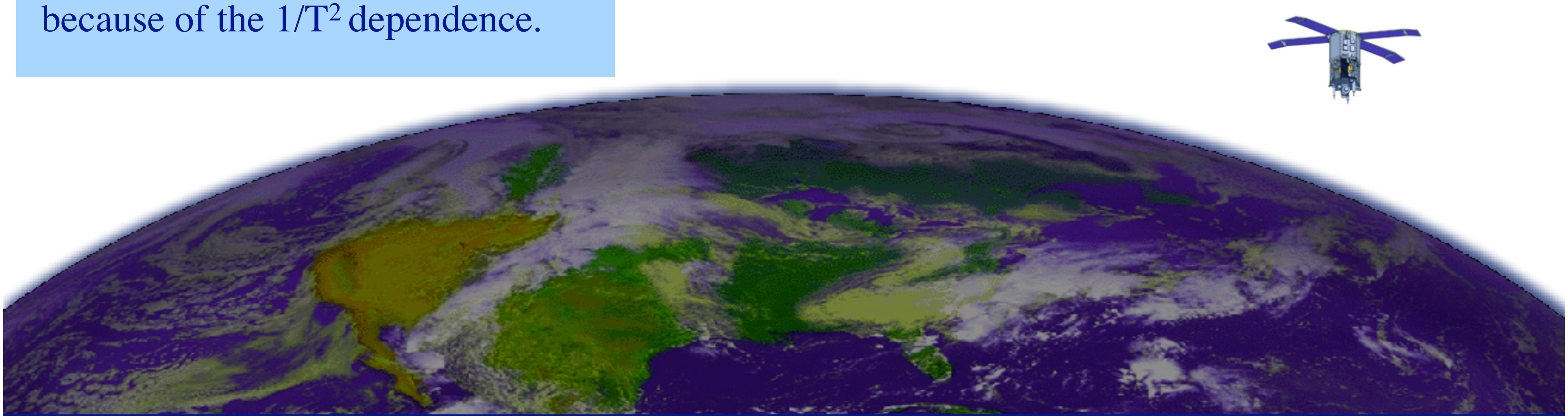
Gradiometer onboard single satellite

Performance expectation with demonstrated technology, assuming 10 s interrogation time, SNR ~ 1000:1, and 10 m baseline separation:

~ $5\mathrm{x}10^{-4}$ E/$\sqrt{\mathrm{Hz}}$;
~ $5\mathrm{x}10^{-5}$ E in a day
~ $3\mathrm{x}10^{-6}$ E in a year.

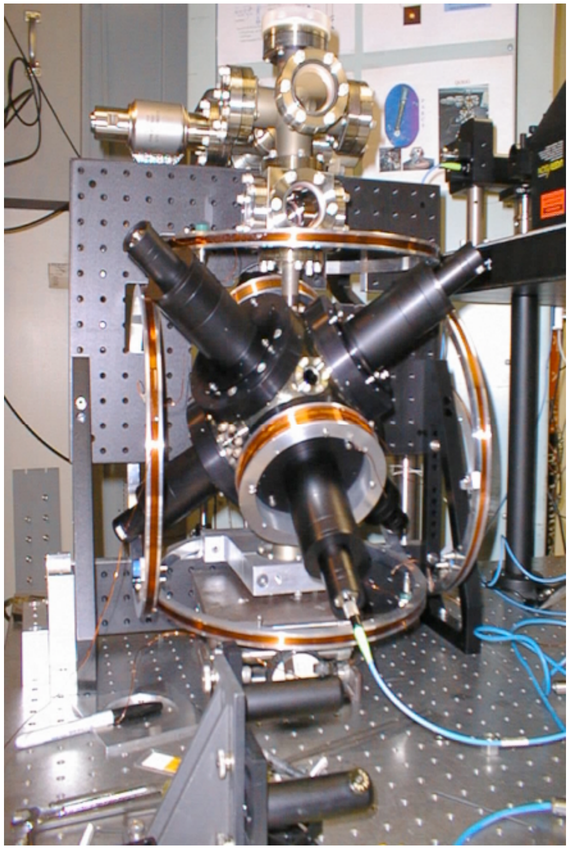
Long baseline (*100 m*): *$5\mathrm{x}10^{-5}$ E/$\mathrm{Hz}^{1/2}$*

Satellite formation (50 km): $1\mathrm{x}10^{-8}$ E/$\mathrm{Hz}^{1/2}$

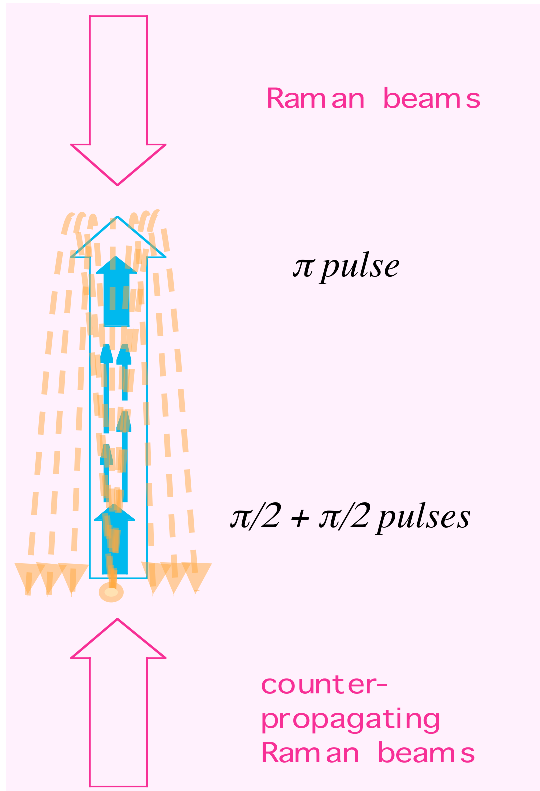


Ground Development
JPL's First Atom Interferometer Demonstration

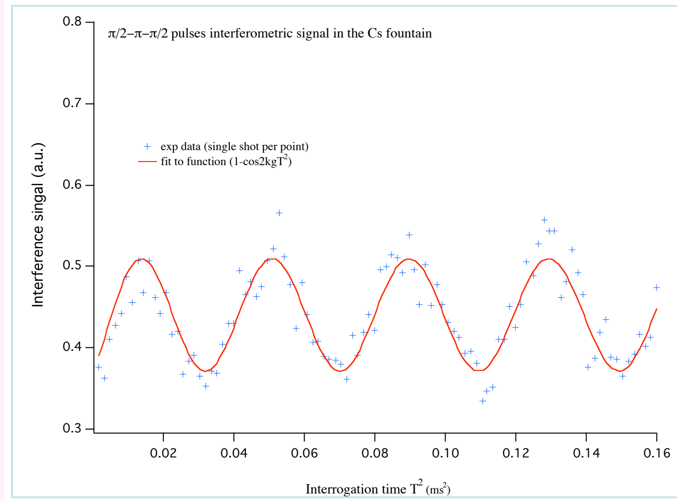
Year 2002



JPL first atomic fountain setup

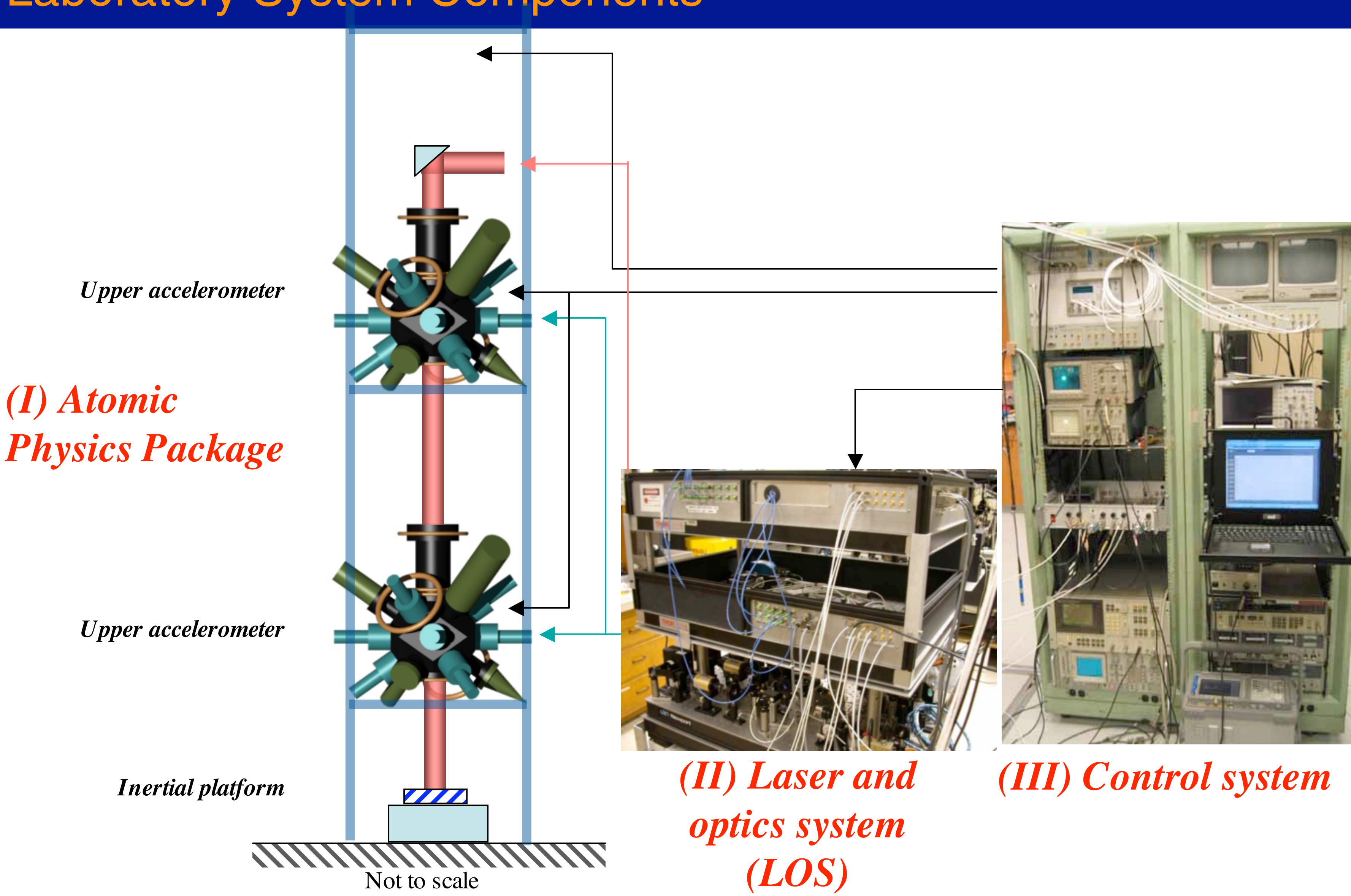


Atomic fountain on ground

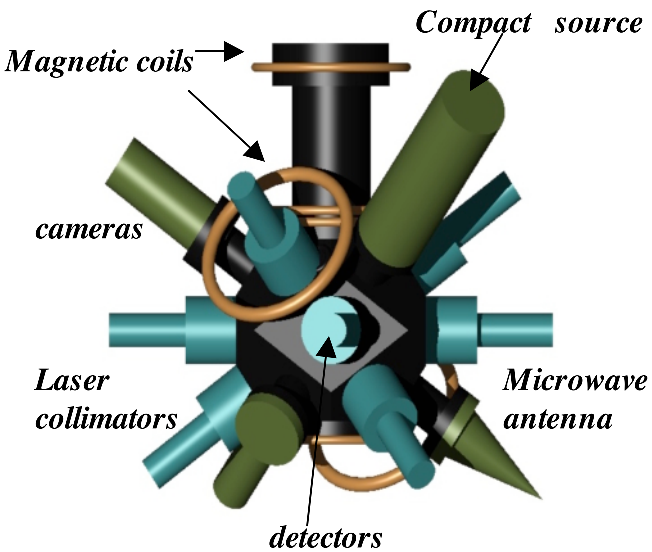


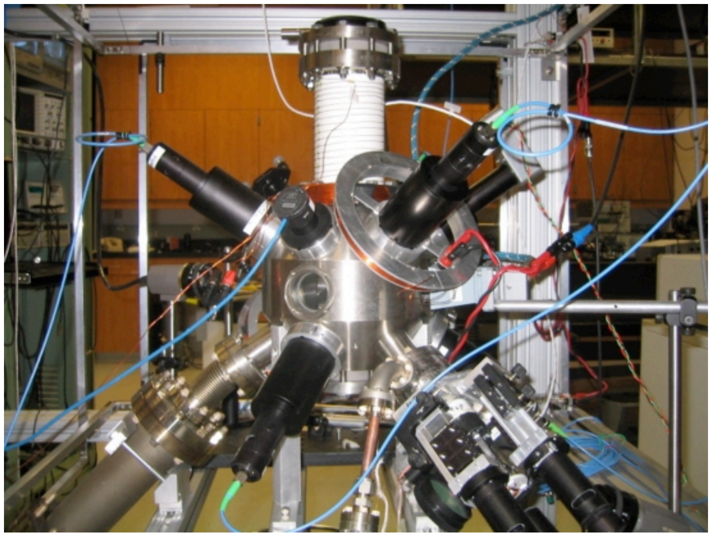
Atom Interferometer Fringe

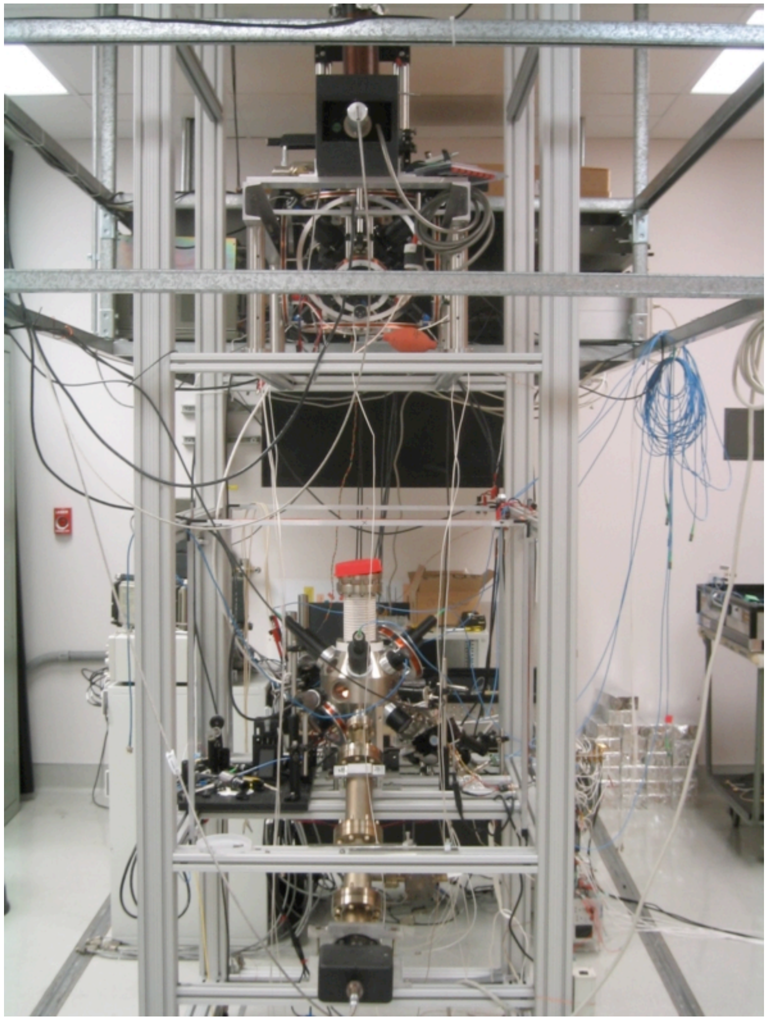
Ground System
Laboratory System Components



Atomic Physics Package
New Vacuum Enclosure

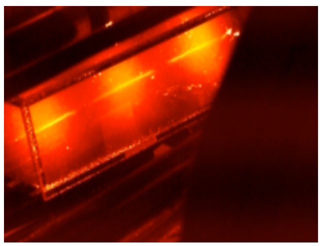


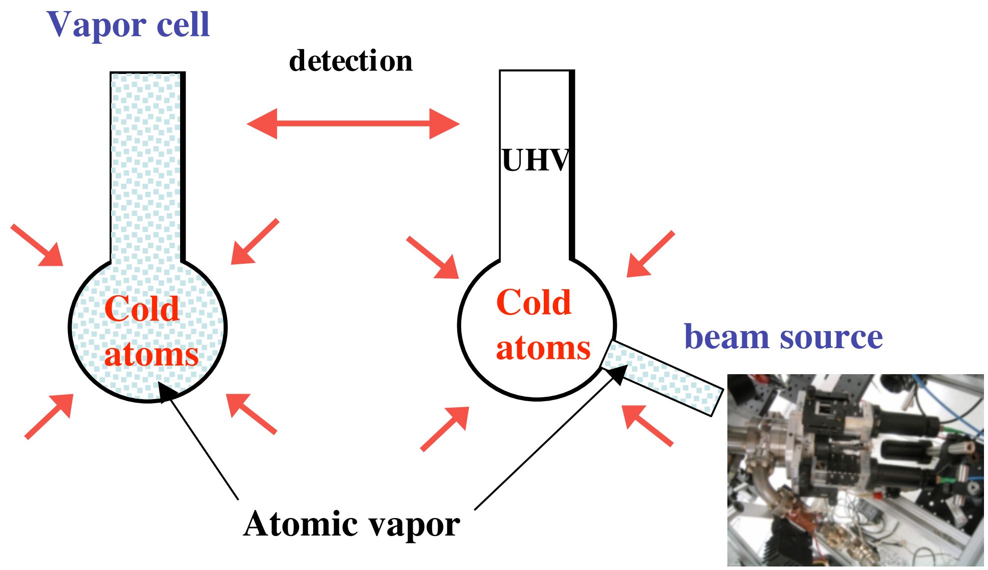


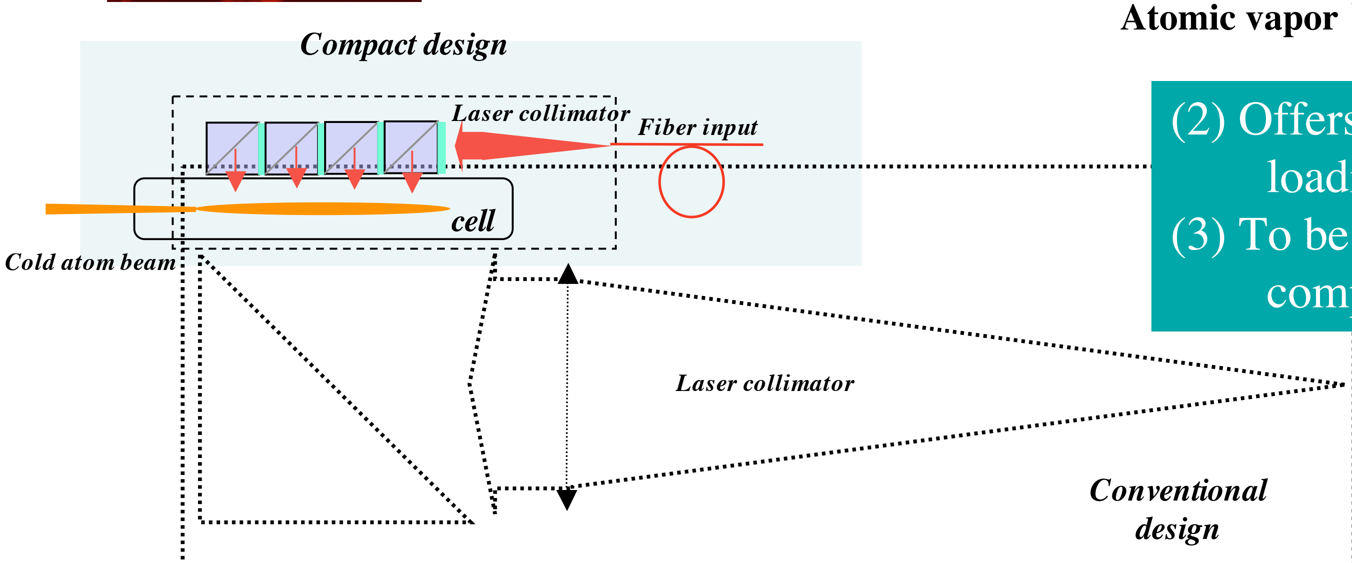


Atomic Physics Package
Advantage of a Compact Cold Atom Source

(1) Allows differential pumping, and hence, UHV interaction and detection regions.





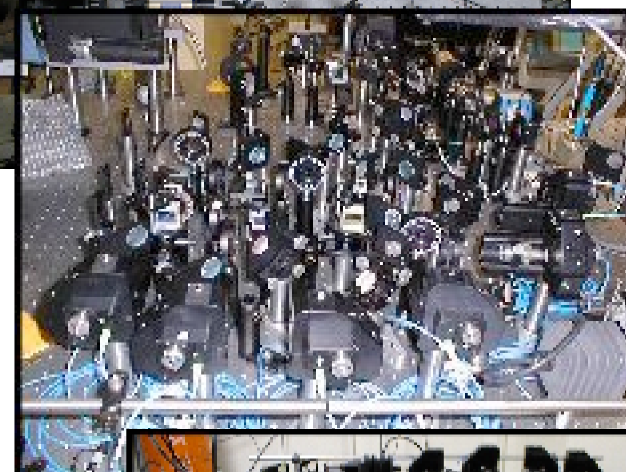
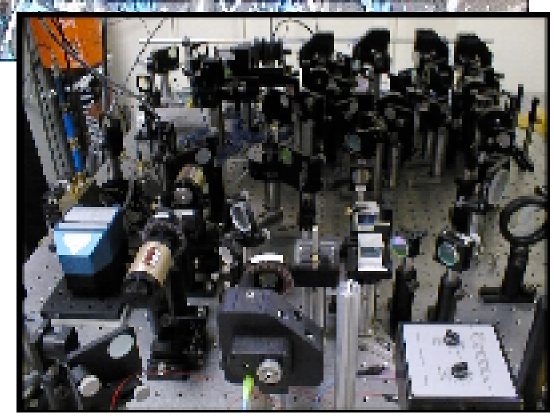
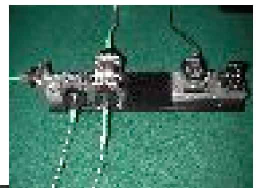
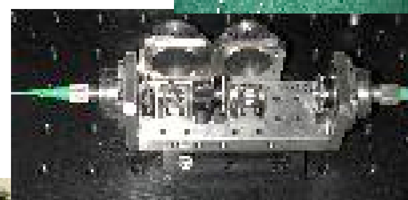


(2) Offers high flux and faster loading.

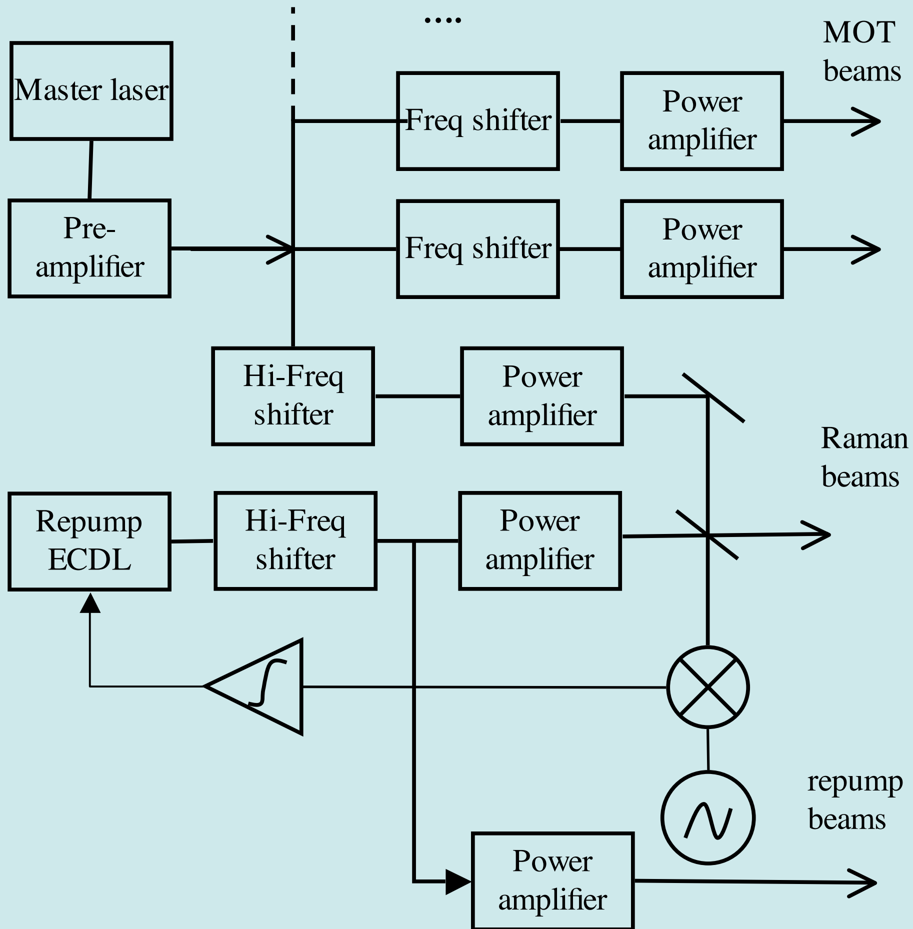
(3) To be used as a simple and compact attachment.

Reducing LOS size
Fiber-linked Compact Modular System

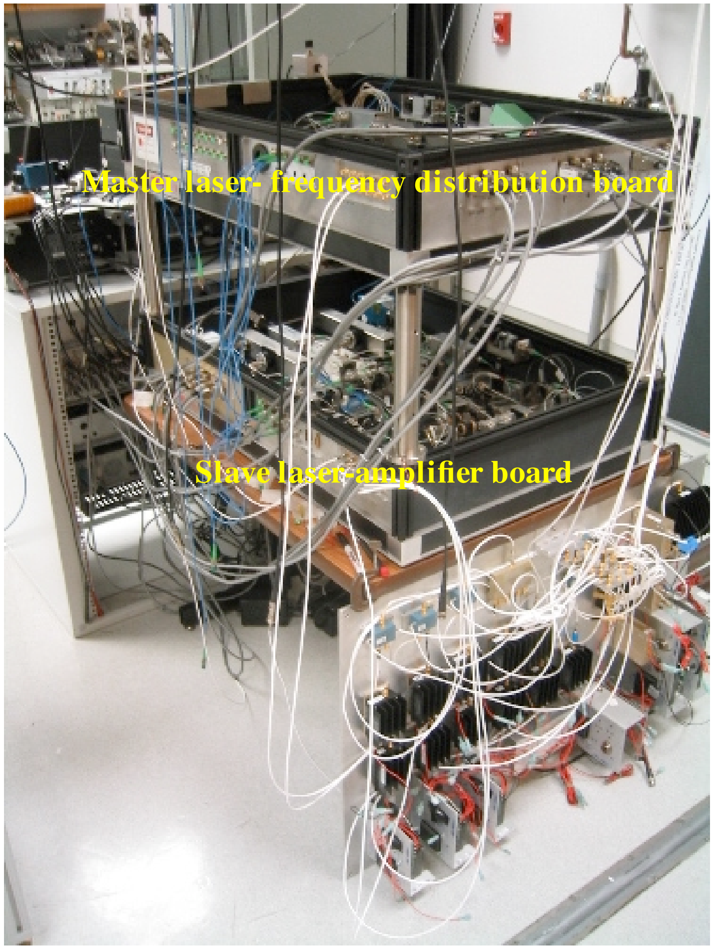
Developing a modularized laser system with extensive use of COTS miniature optics and fiber coupling for beam distribution.


LOS Schematic and Implementation

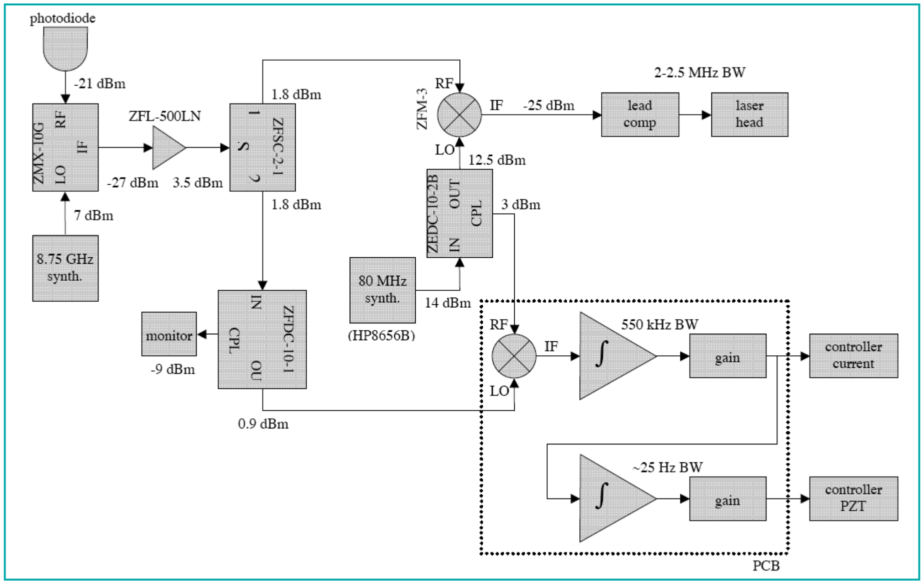


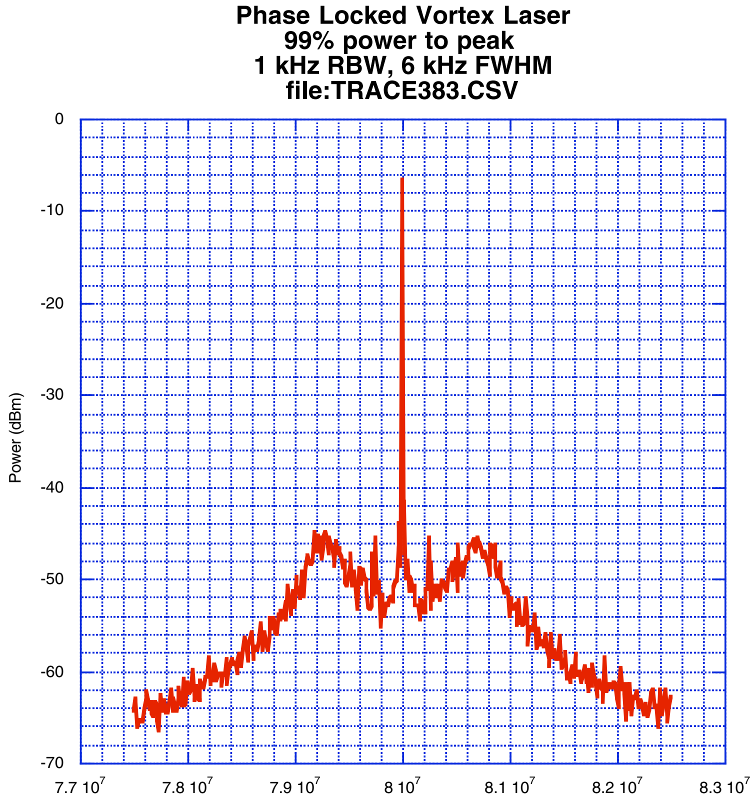
Laser subsystem schematic



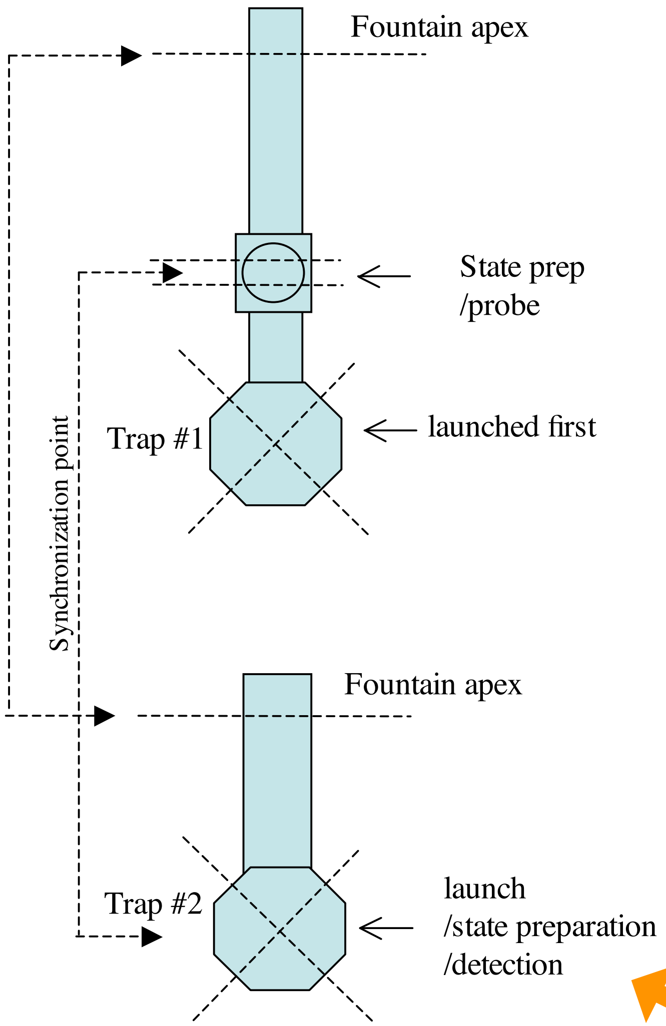
LOS system includes two 2'x3' breadboards. Also shown are the AOM rf drivers.

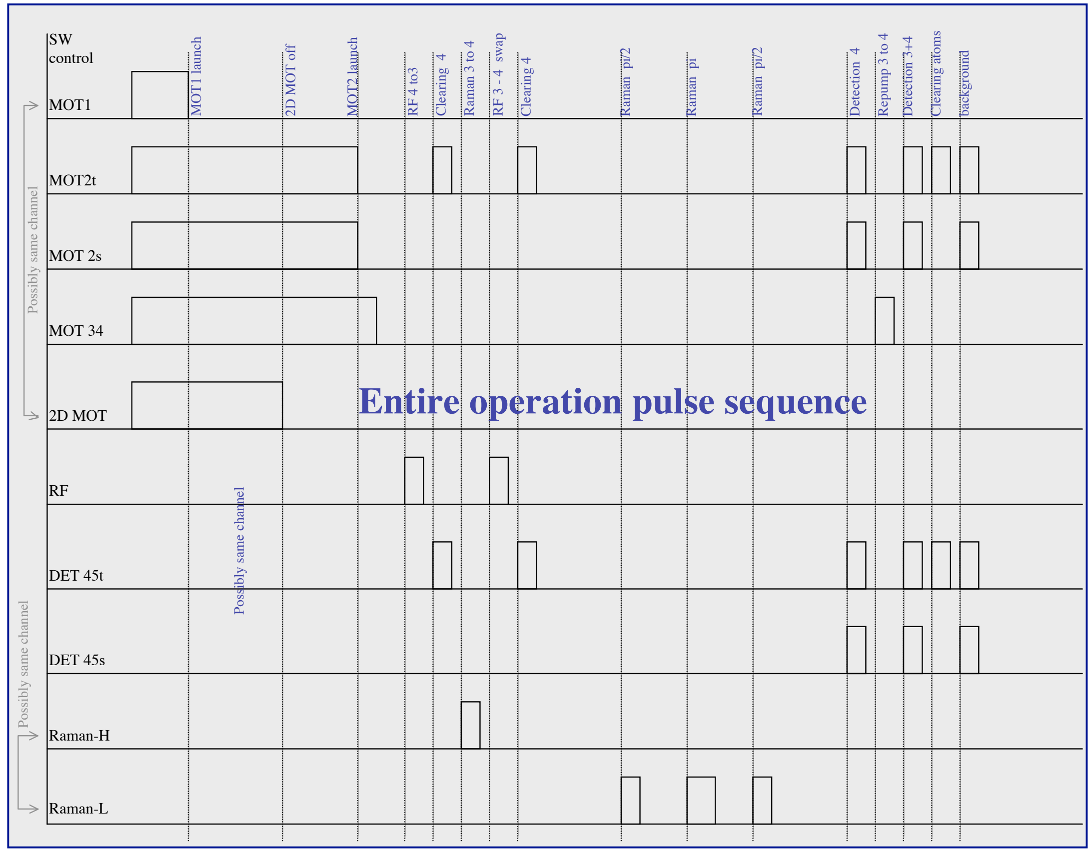
AI (Raman) Lasers
Phase Locking Implementation





AI Operation
Synchronization and New Configuration Geometry



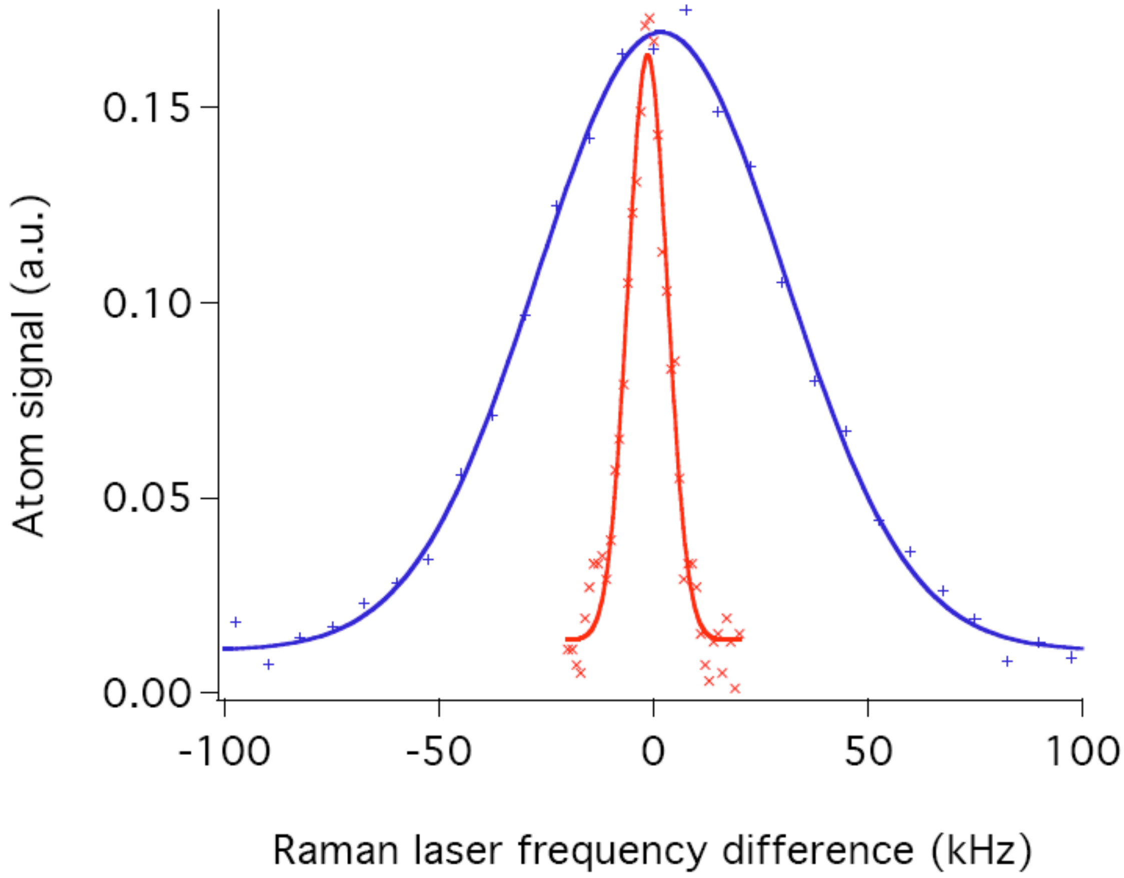


Operation of the atomic fountain/AI operation with only one set of trap laser beams.

Reduced the system complexity and suitable for no-launch operation in space.

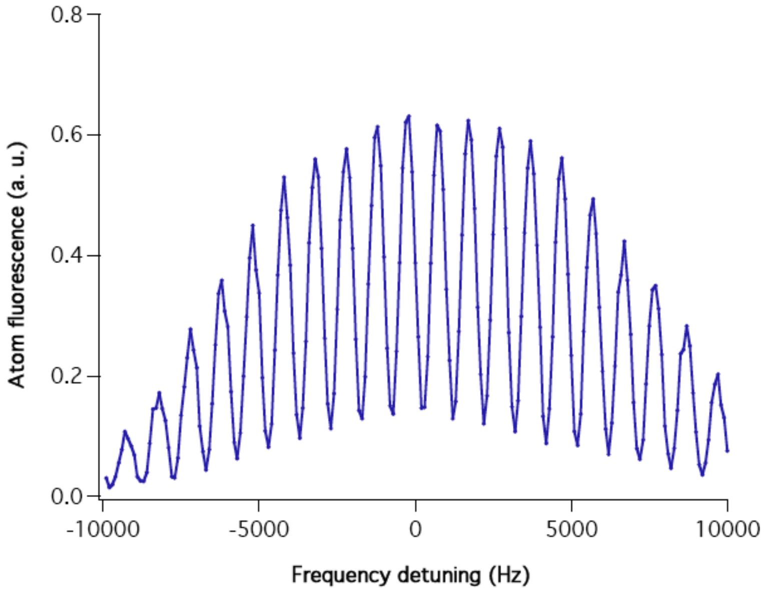
Experiment

Atomic Doppler profile before and after velocity selection

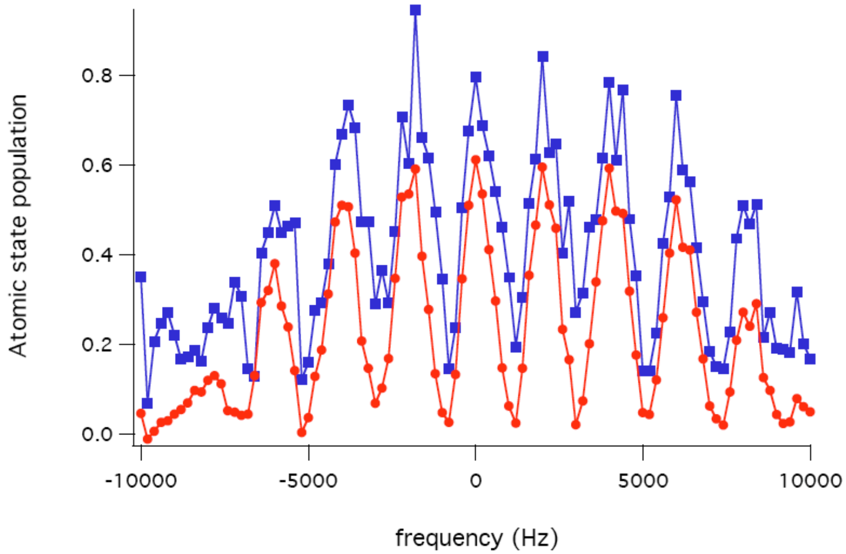


Blue: Doppler profile before velocity selection: 2.8 uK.
Red: an atom cloud of 130 nK 1D temperature after velocity selection.

Experiment
Simultaneous Ramsey fringe measurements

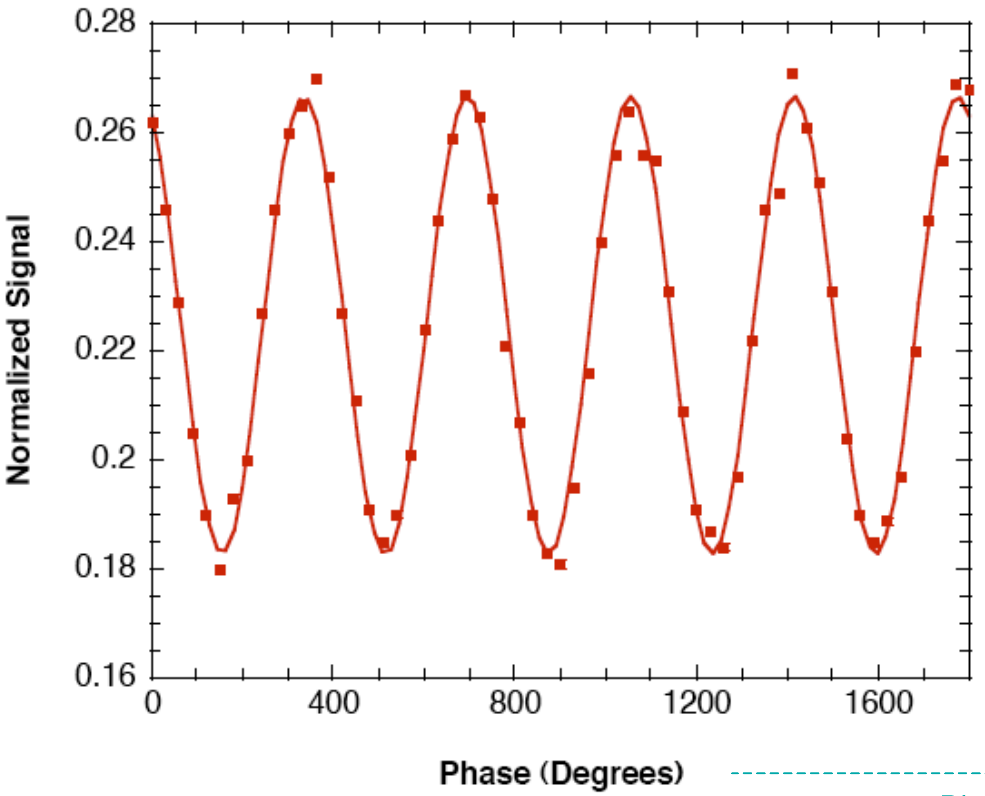


Ramsey Fringes of Doppler-insensitive transition. Up to 200 ms interaction time was used without significant degradation of the fringe contrast.

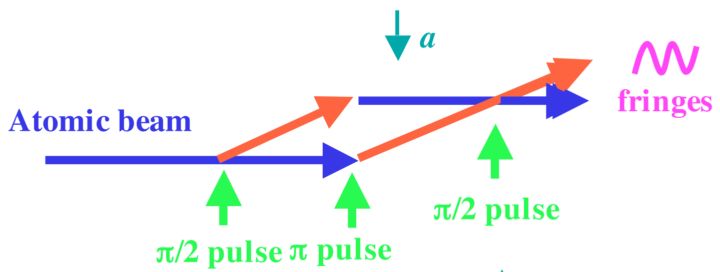


Simultaneous measurement of the Ramsey fringes in two atomic fountains. The plot shows the unprocessed experimental data without averaging (single measurement per point). The red points from the newer Ti-chamber atomic fountain setup.

Experiment
Improved Atom Interferometer Fringe



The interrogation time is under 10 ms for obtaining high contrast fringes, limited by environment vibrations.



Phase stepped in the last Raman pulse

Summary

- Atom interferometer is a new inertial sensing technology that can significantly benefit Earth Science and solid Earth investigations.
- Significant progress has been made in the development of a laboratory prototype with all major subsystems (new physics package, compact laser and optics system, and rf and control electronics) completed.
- Obtained high fringe contrast in both Doppler insensitive and sensitive fringes. Also made preliminary differential measurements of two atom interferometers.
- Currently are working towards the final demonstration and evaluation of the gravity gradiometer.
- Special issues related to operating in space with long interrogation time are being studied (but not discussed in the talk).
- A follow-on IIP hardware development will be an instrument prototype that can be tested in the field or airborne to bring the technology maturity to TRL-6, which will build the more confidence in the Earth Science community.
- Our goal is to have a space-borne opportunity for a global gravity mapping mission and demonstrate the benefit of the atom-interferometer technology.